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IN THE NAME OF

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FOR

SINGLE-BODY DUAL-CHIP ORTHOGONAL SENSING TRANSIT-TIME FLOW DEVICE USING A PARABOLIC REFLECTING SURFACE

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TITLE

SINGLE-BODY DUAL-CHIP ORTHOGONAL SENSING TRANSIT-TIME FLOW DEVICE USING A PARABOLIC REFLECTING SURFACE

RELATED APPLICATIONS

5   This application is a continuation-in-part of U.S. patent application ser. no. 10/331,950, filed December 30, 2002, the disclosure of which is incorporated herein by reference.

BACKGROUND

1.   Technical Field

An embodiment of the present invention generally relates to an ultrasonic flow sensor.

10   More particularly, an embodiment of the present invention relates to a transit-time ultrasonic flow sensor with a parabolic reflecting surface to measure a flow rate.

2.   Discussion of the Related Art

The use of the insertion monitoring devices to measure fluid flow rate are restricted by cost and practical problems. For example, in one known insertion metering device, a probe is

15   inserted into a duct through a hole or valve opening in the duct wall. The probe comprises a rod which carries a turbine or electromagnetic sensing element on its tip. The sensing element can take a point measurement indicative of the flow in a part of the duct at a point in time. However, because the flow in the duct is unknown, (varying both in profile across the cross-section of the duct and with time) several measurements must be taken at different points in the cross-section

20   of the duct and at different times. An average can then be built up which would approximate the average flow rate. Its accuracy is limited by the difficulty in aligning the sensing element correctly along the axis of the duct.

In order to obtain reasonably accurate results, the prior art insertion technique requires that measurements be taken at several positions across at least one diameter of the duct. However, it has been found that in practice where flow profiles are distorted, it is necessary to measure across more than one diameter (i.e. two orthogonal diameters) to provide sufficiently

5   accurate results which can be used for calibration. This introduces severe problems when the duct system is installed underground, as it requires that a large chamber must be excavated around the duct in order to allow access for separate circumferentially spaced holes in the duct to be made to allow the orthogonal measurements to be made. Additional problems may be encountered with duct systems installed in aircraft where access may also be difficult.

10   A further problem with the prior art technique is that the surface area of the rod which supports the sensing element forms a variable blockage in the duct as the element is moved across the diameter. This blockage affects the results by altering the flow profile in the duct and increases turbulence. Furthermore, the process of taking the many measurements required is subject to variability due to the often difficult operating conditions in which the measurements

15   must be made. For example, the insertion probe operator may be working in a water filled, muddy pit which makes it difficult to obtain the various readings with any certain degree of accuracy.

Several different sensor configurations have also been used including: 1) direct measurement of a propagation time of a pulse emitted by a first transducer and received by a

20   second transducer, where the change in time is a function of fluid flow rate; 2) dual "sing-around" sound velocimeters, where the difference in "sing-around" frequency between the velocimeters is a function of the fluid flow rate; 3) sensors producing continuous waves using two widely different high frequency carriers but commonly modulated with another much lower

frequency signal, where the phase difference of the modulated signal on the received carriers is a function of the fluid flow rate; and 4) sensors producing bursts of continuous waves, using a single frequency on a pair of transducers, the burst duration being less than the acoustic propagation time between the transducers, where the time between the received transmissions is

5   a function of flow rate.

Transit-time ultrasonic flow sensors, also known as "time-of-flight" ultrasonic flow sensors, detect the acoustic propagation time difference between upstream and downstream ultrasonic transmissions, resulting from movement of flowing fluid, and process this information to derive a fluid flow rate.

10   Transducers of transit-time ultrasonic flow sensors are most often field mounted. They are generally individually attached to the outside of a pipe. Unlike other types of ultrasonic flow sensors, such as Doppler ultrasonic flow sensors, transit-time ultrasonic flow sensors typically do not require placing a transducer inside a pipe in order to make a flow measurement. However, measurement accuracy may be compromised by a multitude of factors, such as pipe wall

15   integrity, pipe surface condition, and distance between transducers.

Even when the transducers are in contact with the fluid being measured (wetted), the transducers may become misaligned, i.e., disposed at the wrong distance or angle, resulting in measurement error. Thus, sensors having wetted transducers are typically equipped with supporting electronics that include sophisticated diagnostics for confirming proper installation

20   and operation. Consequently, such sensors are relatively expensive and have a reputation for occasionally producing erroneous measurements.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 illustrates an ultrasonic flow sensor and a curved reflecting surface according to an embodiment of the present invention;

Figure 2 illustrates transducer impedance matching according to an embodiment of the present invention;

Figure 3A illustrates an ultrasonic flow sensor including a plastic end cap according to an embodiment of the present invention;

Figure 3B illustrates an ultrasonic flow sensor including a metal end cap according to an embodiment of the present invention;

Figure 3C illustrates an ultrasonic flow sensor without an end cap according to an embodiment of the present invention;

Figure 4 illustrates curved reflecting surfaces according to embodiments of the present invention;

Figure 5 illustrates an ultrasonic sensor system according to an embodiment of the present invention;

Figure 6 illustrates an ultrasonic sensor installed into an existing duct assembly according to an embodiment of the present invention;

Figure 7 illustrates an ultrasonic flow sensor including an end cap according to an embodiment of the present invention;

Figure 8 illustrates a retrofit assembly including a boot structure with a mounting flange according to an embodiment of the present invention; and

Figure 9 illustrates a flow chart diagram for a method of installing an ultrasonic sensor into an existing duct assembly according to an embodiment of the present invention.

DETAILED DESCRIPTION

Reference in the specification to "one embodiment", "an embodiment", or "another embodiment" of the present invention means that a particular feature, structure or characteristic described in connection with the embodiment is included in at least one embodiment of the

5   present invention. Thus, appearances of the phrase "in one embodiment" or "according to an embodiment" appearing in various places throughout the specification are not necessarily all referring to the same embodiment. Likewise, appearances of the phrase "in another embodiment" or "according to another embodiment" appearing in various places throughout the specification are not necessarily referring to different embodiments.

10   Referring to Figure 1, embodiments of the present invention are directed to an ultrasonic sensor 100 adapted to be inserted into a duct, a manifold, or a pipe 130 (hereinafter referred to as a "duct"). The ultrasonic sensor 100 having ultrasound transducers 105, 110 and being able to perform at a single site of introduction into the duct 130. The flow sensor measures a forward ultrasonic path transit time having a component of travel of ultrasound in a forward direction

15   relative to a fluid flow 155, i.e., an axial direction relative to the region of the duct 130 where the sensor 100 is inserted, and also being able to perform a second reverse path transit time measurement having a component of travel of ultrasound in a second axial direction opposite to the first axial direction. The arrangement being such that a comparison of the signal associated with ultrasound travel in one axial direction with that of the signal associated with ultrasound

20   travel in the opposite axial direction enables the flow rate of fluid in the duct, manifold, or pipe to be determined.

The ultrasonic sensor 100 requires at least one ultrasound transmitter and detector pair 105, 110 for each forward or reverse measurement. Embodiments of the present invention use

the same transducer 105, 110 to transmit and detect. Therefore, two transducers 105, 110 each capable of transmitting and detecting may measure both the forward and the reverse transit times.

5   Embodiments of the present invention may use piezoelectric transducers to generate or receive the ultrasound/acoustic signals. A piezoelectric transducer converts electrical signals into mechanical vibrations (transmitter) and mechanical vibrations into electrical signals (receiver). In the case of a receiver, piezoelectric transducers convert force or mechanical stress into electric charge which in turn may be converted into a voltage. For a transmitter, a voltage is applied to a piezoelectric transducer wherein the resultant electric field causes a deformation of 10   the crystal material to generate an acoustic signal.

The thickness of a piezoelectric transducer is determined by a desired frequency of operation of the transducer. A thin crystal wafer (active element) vibrates generating an acoustic wave with a wavelength that is twice the thickness of the transducer crystal. Therefore, transducer piezoelectric crystals are cut to a thickness that is ½ the desired radiated wavelength. 15   The higher the desired frequency of operation of the transducer, the thinner the active element. The frequency range of the ultrasound signals may be, for example, up to 5 Mhz.

Referring to Figure 1, the first transducer 105 may comprise the transmitter of one forward path transmitter/receiver pair and the receiver of another reverse transmitter/receiver pair. The second transducer 110 may comprise the receiver of the forward transmitter/receiver 20   pair and the transmitter of the reverse transmitter/receiver pair.

Referring to Figure 2, ultrasonic waves are reflected at boundaries where there are differences in acoustic impedance (Z). This is commonly referred to as impedance mismatch. A value for a fraction of an incident-wave intensity in a reflected wave can be derived because

particle velocity and local particle pressures are required to be continuous across a boundary between materials. The fraction of the incident-wave intensity in reflected waves being directly proportional to a wavelength of a particular wave mode. At narrow frequency bands, efficient transmission may be achieved between two media of different acoustic impedances. To

5 maximize an amount of energy transmitted out of a transducer and into a medium, an impedance matching layer is placed between the active element/transducer and the medium through which the ultrasound wave is to propagate.

In an embodiment of the present invention, the matching layer is made from a material, for example a plastic, that has an acoustic impedance approximately equal to a value between the

10 acoustic impedance of the transducer and the acoustic impedance of a liquid such as an oil. The equation for calculating the acoustic impedance of the matching layer is given by:

$$Z_{matchinglayer} = (Z_{transducer}Z_{oil})^{1/2}$$

Referring to Figure 2, three medium are illustrated having three different acoustic impedances. Medium 1 may be thought of as the piezoelectric transducer with an acoustic

15 impedance $Z_1 = Z_{transducer}$, medium 2 may be the matching layer with an acoustic impedance $Z_2 = Z_{matchinglayer}$, and medium 3 may be a liquid such as an oil with an acoustic impedance $Z_3 = Z_{oil}$. Optimal impedance matching is achieved by sizing the matching layer so that a wave, that is reflected from the matching layer/oil boundary and then again from the matching layer/transducer boundary, is in phase with other cycles of the transmitted ultrasound when the

20 matching layer thickness is 1/4 wavelength. This keeps waves that are reflected within the matching layer in phase when they exit the layer as illustrated in Figure 2.

The above relationship holds true when there is a pressure inversion at the first reflection boundary due to $Z_{matchinglayer} > Z_{oil}$ and no pressure inversion at the second reflection boundary

due to $Z_{matchinglayer} < Z_{transducer}$. The pressure inversion at the first reflection boundary and no pressure inversion at the second reflection boundary allows the reflected ultrasonic wave to be in phase with other cycles of the transmitted ultrasound when the matching layer thickness is 1/4 wavelength.

5   In an embodiment of the present invention as shown in Figure 3A, the piezoelectric transducers are placed in an end cap made of a plastic having an acoustic impedance $Z_{matching\ layer}$ less than that of the piezoelectric transducer $Z_{transducer}$ and greater than that of an oil Z_{oil}, wherein the plastic serves as the matching layer.

      In an alternative embodiment of the present invention as shown in Figure 3B, the

10   piezoelectric transducer is placed in an end cap made of a metal having an acoustic impedance $Z_{metal} = Z_{matchinglayer}$ greater than that of the piezoelectric transducer $Z_{transducer}$ and greater than that of an oil Z_{oil}, wherein the metal serves as the matching layer. In this case, there is a pressure inversion at the first reflection boundary due to $Z_{matchinglayer} > Z_{oil}$ and a pressure inversion at the second reflection boundary due to $Z_{matchinglayer} > Z_{transducer}$. The pressure inversion at the first

15   reflection boundary and the pressure inversion at the second reflection boundary allows the reflected ultrasonic wave to be in phase with other cycles of the transmitted ultrasound when the matching layer thickness is 1/2 wavelength.

      In addition, optimum resonant reflection may occur when an ultrasonic wave propagating through a liquid impinges upon an end cap made of metal, when the end cap metal thickness is

20   equal to approximately $(3/4 + n/2)\lambda$.

      Referring to Figure 3A, the two transducers 105, 110 are mounted and spaced apart by a distance L_1 within a housing 111. A plastic end cap 115 is hermetically sealed to the housing

111 to enclose and isolate the transducers 105, 110 from the flowing fluid 155. A distance L_2

between the end cap surface 116 in contact with the flowing fluid 155 and the emitting surface of

the transducers 105, 110 is equal to $(n/4)\lambda$, where λ is a wavelength of the transmitted signal, and

n is an integer. For example, resonance transmission of an acoustic signal occurs for n = 1 and

5      $L_2 = 1/4 \lambda$. A distance L_3 between the end cap surface 116 in contact with the flowing fluid 155

and a point on the housing 111 located between the transducers 105, 110 is equal to $(3/4 + n/2)\lambda$,

where λ is a wavelength of the transmitted signal, and n is an integer. For example, resonance

reflection of an acoustic signal occurs for n = 2 and $L_3 = 1.75 \lambda$.

Referring to Figure 3B, the two transducers 105, 110 are mounted and spaced apart by a

10   distance L_1 within a housing 111. A metal end cap 115 is hermetically sealed to the housing 111

to enclose and isolate the transducers 105, 110 from the flowing fluid 155. A distance L_2

between the end cap surface 116 in contact with the flowing fluid 155 and the emitting surface of

the transducers 105, 110 is equal to $(n/2)\lambda$, where λ is a wavelength of the transmitted signal, and

n is an integer. For example, resonance transmission of an acoustic signal occurs for n = 1 and

15     $L_2 = 1/2 \lambda$. A distance L_3 between the end cap surface 116 in contact with the flowing fluid 155

and a point on the housing 111 located between the transducers 105, 110 is equal to $(3/4 + n/2)\lambda$,

where λ is a wavelength of the transmitted signal, and n is an integer. For example, resonance

reflection of an acoustic signal occurs for n = 2 and $L_3 = 1.75 \lambda$.

Referring to Figure 3C, an alternative embodiment of the present invention may have the

20   transducers 105, 100 disposed in a recess 320 in a metal housing 311 of an ultrasonic sensor 300.

This eliminates the use of the end cap 115 as shown in Figure 1. A reflective surface 316 of the

metal housing 311 adjacent the active transducer surfaces 105, 110 may be in contact with a

fluid. The reflective surface 316 of the housing 311 being $1/2 \lambda$ away from the active transducer

surfaces 105, 110 and a distance between the reflective surface 316 and a point 315 on the

housing 311 located between the transducers 105, 110 is equal to 1.75 λ.

Referring to Figure 2, the backing material supporting the crystal has a great influence on

damping characteristics of the active element transducer. Using a backing material with

5   impedance similar to that of the active element/transducer will produce the most effective

damping. Embodiments of the present invention may have a narrow bandwidth resulting in

higher sensitivity. As the mismatch in impedance between the active element and the backing

material increases, material penetration increases while transducer sensitivity is reduced.

Referring to Figure 1, the ultrasonic sensor 100 is adapted to measure the transit times of

10   an ultrasonic pulse in the forward and reverse directions of a W shaped path 190 or a V shaped

path 191. The transit time difference in the forward and reverse directions of ultrasound travel

along the W paths 190 or V paths 191 may be used to calculate the flow rate of fluid in the duct

130.

To calculate the flow rate from the transit times along each W shaped 190 or V shaped

15   191 transmission path, the difference between the transit times in the directions along the paths

in the forward and reverse times may be used. An approximately proportional relationship exists

between transit time and flow. For example, for a V shaped path:

$$V = K*D/\sin2\Theta * 1/(T_o - \tau)^2 * \Delta T$$

Where:

20   V = mean velocity of flowing fluid

K = constant

D = inner diameter of pipe or duct

Θ = incident angle of ultrasonic signal

T_o = Zero flow transit time

$\Delta T = T_2 - T_1$

T_1 = transit time of acoustic signal from upstream transducer to downstream transducer

T_2 = transit time of acoustic signal from downstream transducer to upstream transducer

5 τ = transit time of acoustic signal through pipe or duct wall and lining

In addition to the above formula, the flowing fluid velocity (V_f) can be determined by the

following equation:

$$V_f = Kdt / T_L$$

where K is a calibration factor for the volume and time units used, dt is the time differential

10 between upstream and downstream transit times, and T_L is the zero-flow transit time.

Theoretically, transit-time ultrasonic meters can be very accurate (inaccuracy of ±0.1% of

reading has been reported). The error in these measurements is limited by both the ability of the

signal processing electronics to determine the transit time and by the degree to which the

electrical signal used to generate the acoustic signal is constant i.e, a sonic velocity (C) that is

15 constant. The speed of sound in the fluid is a function of the stability of the electrical signal used

to generate the acoustic signal, the density of the fluid and the temperature of the fluid.

Therefore, relatively simple electronic circuitry may be employed to extract flow data.

For example, an electronic transmitting and receiving device 200 may be used, connected to the

transducers 105, 110 via wires 112 which pass through the housing 111 and may be sealed by

20 epoxy. The electronics 200 may be connected after the flow sensor 100 is inserted (see Figure

3A).

Preferably the fluid flow sensor 100 i.e., the transducer pair 105, 110 contained within the

end cap 115, are adapted to be flush with a wall of the duct 130 in use. This reduces the

disturbance of the fluid flow to provide a higher accuracy measurement of the fluid flow rate (see also Figure 5).

Because the ultrasound path has at least two path environments (forward and reverse W paths 190, or forward and reverse V paths 191) and the ultrasound travels through the fluid in the

5   duct axially (at least with an axial component), the fluid flow at several different points on the ultrasound path affects the signal that is measured. This provides a degree of built-in averaging or integration which eliminates the need to obtain many measurements at different points in the cross-section of the duct. Therefore, an amount of integration of the signal is inherently present, which provides a more accurate indication of flow rate than single point measurements. In

10   addition, because there is no need to make measurements at different points, the sensor does not need to be moved which simplifies the operation. A longer acoustic path provides a more accurate indication of flow rate. Therefore, a W shaped path provides a more accurate indication of flow rate than does a V shaped path.

Referring to Figure 1, preferably, the ultrasonic sensor 100 is adapted to use the reflection

15   of the ultrasound off of a curved reflecting surface 120 on a wall of the duct 130 and a reflective surface 116 of the end cap 115 (or the reflective surface 316 of the housing 311 as shown in Figure 3C) to create the forward W shaped ultrasonic path 190 and the reverse W shaped ultrasonic path 190. The ultrasonic paths are beams of ultrasound. The ultrasonic sensor 100 operates to take the forward and reverse ultrasonic path measurements from a stationary position.

20   In a prior art transit time flow sensor, the choice of length L_1 between the first transducer 105 and second transducer 110 is dependent upon the diameter of the duct and orientation angle α 157 of the transducers 105, 110. In use, signals are transmitted along paths between the transducers 105, 110, and in order for the first and second transducers 105, 110 to communicate

when used in, for example, a circular duct 130, the relation $L_1 = 3 \tan \alpha\, D$ is preferable, where D

is the duct diameter and α 157 is the angle of inclination of the acoustic paths relative to axis 150

orthogonal to the central axis 156 of the duct 130. This relationship arises because of the angle

of reflection of the signal from the duct wall or walls.

5   As an example, given a duct diameter D = 10 inches, if the angle of inclination α 157 is

one degree, the signal path is one degree relative to axis 150 orthogonal to the central axis 156 of

the duct 130, and the separation L_1 between the first transducer 105 and second transducer 110 is

equal to approximately 1/2 inch.   From the above, the length L_1 should be correctly set for

different duct diameters and should be adjustable if the sensor assembly is to be suitable for use

10   with any duct diameter.

Figure 1 illustrates a flow sensor 100 utilizing a parabolic or spherical reflecting surface

120 according to an embodiment of the present invention. The parabolic or spherical reflecting

surface 120 is located on the duct 130 wall opposite the transducers 105, 110. The transducers

105, 110 are oriented at an angle alpha 157 approximately equal to zero relative to the axis 150

15   orthogonal to the central axis 156 of the duct 130. Therefore, the initial path is in effect

orthogonal to the duct axis 156. However, the pair of transducers 105, 110 need not be

absolutely adjacent one another (i.e. $L_1 \neq 0$) because the acoustic signal diffracts (beam spreads)

as it leaves the transducers 105, 110. In addition, the parabolic or spherical reflecting surface

120 serves to both redirect and image the acoustic signal.

20   Referring to Figure 4, the equation for a circular cross-section of a sphere

is given by

$$x^2 + (y - R)^2 = R^2 \qquad \text{equation 1}$$

where the center C is shifted from the origin O by one radius R. Rewriting this equation as

$$x^2 - 2Ry + y^2 = 0$$

and solving for x:

5 $$y = R \pm (R^2 - x^2)^{\frac{1}{2}} \qquad \text{equation 2}$$

For values of y less than R, a hemisphere, open on the top, corresponding to the minus sign in equation 2 above, is shown at the top of Figure 4. After expansion in a binomial series, y takes the form

10 $$y = \frac{x^2}{2R} + \frac{1x^4}{2^2 2! R^3} + \frac{1 \cdot 3x^6}{2^3 3! R^5} + \cdots. \qquad \text{equation 3}$$

Equation 3 becomes important when compared to the standard equation for a parabola with its vertex at the origin and its focus a distance f in the vertical direction as shown below as equation 4 and equation 5. See middle of Figure 4.

$$x^2 = 4fy \qquad \text{equation 4}$$

15 $$y = x^2/2R \qquad \text{equation 5}$$

If $4f = 2R$ (i.e., if $f = R/2$) is substituted into equation 4 and subsequently rewritten as equation 5, it is apparent that when comparing equation 3 and equation 5, the first contribution in the series of equation 3 can be thought of as parabolic (equation 5), and the remaining terms represent the deviation. If that deviation is Δy, then

20 $$\Delta y = \frac{x^4}{8R^3} + \frac{x^6}{16R^5} + \cdots. \qquad \text{equation 6}$$

This difference will be appreciable only when x is relatively large (see top of Figure 4) in comparison to R. In the paraxial region, i.e., in the immediate vicinity of the central axis of the parabola, these two configurations (parabola versus hemisphere) will be essentially

25 indistinguishable.

When the acoustic signals are reflected with a flat reflecting surface, the received signal is a summation of the transmitted signal having taken more than one path because of diffraction (beam spreading). The relative magnitudes and phase relationships of the components of the received signal may cause increased noise and drift in the flow rate output signal. Referring to

5   Figure 1 and Figure 4, this problem may be reduced by curving the reflecting surface 120 facing the transducers in the direction along the axis 150 between the transducers 105, 110 using, for example, a spherical reflecting surface with a radius of curvature equal to approximately two times a focal distance, where the focal distance defines the distance along the axis 150 (between the transducers 105, 110) separating a reflective point 117 on the reflective end cap surface 116

10   (or the reflective surface 316 of the housing 311 as shown in Figure 3C) and the center of the spherical reflecting surface 120.

Alternatively, a parabolic reflecting surface may be formed according to the standard equation 4 for a parabola discussed above. The focal distance of the parabola defines the distance along the axis 150 (between the transducers 105, 110) separating a reflective point 117

15·   on the reflective end cap surface 116 (or the reflective surface 316 of the housing 311 as shown in Figure 3C) and the center of the parabolic reflecting surface 120.

Because the degree of curvature for a spherical or parabolic reflecting surface is small, it should not affect fluid flow sensing in most applications. The inside surface of a pipe would not provide the same benefit because its curvature is orthogonal to that desired.

20   Referring to Figure 1 and Figure 3C, for an embodiment using a parabolic or spherical reflecting surface 120, the first 105 and second 110 transducers launch acoustic signals at an angle alpha 157 approximately equal to zero, the acoustic signals impinge upon the parabolic or spherical reflecting surface 120. Specifically, the first transducer 105 launches a forward

traveling acoustic signal at an angle alpha 157 approximately equal to zero into the duct which

propagates through a forward traveling fluid 155 contained in the duct 130 until the acoustic

signal reflects off of the parabolic or spherical reflecting surface 120. The acoustic signal is then

re-directed back towards the flow sensor 100 (flow sensor 300) until it makes a second reflection

5   off of the end cap surface 116 (or the reflective surface 316 of the housing 311 as shown in

Figure 3C). This reflection takes place at a reflection point 117 located on the end cap 115

midway between the central axis of the first 105 transducer and the central axis of the second

110 transducer and occurs at an angle beta (or at a reflection point 317 located on the reflective

surface 316 of the housing 311 as shown in Figure 3C midway between the central axis of the

10   first 105 transducer and the central axis of the second 110 transducer). The acoustic signal is

then re-directed back towards the parabolic or spherical reflecting surface 120 to make a third

reflection off of the parabolic or spherical reflecting surface 120. Again, the acoustic signal is

then re-directed back towards the flow sensor 100 until it then passes through the end cap surface

116 (or reflective surface 316) to reach the second transducer 110 also oriented at an angle alpha

15   157 approximately equal to zero.

The reverse W path 190 is similar. The second transducer 110 launches a reverse

traveling acoustic signal into the duct 130 which propagates through the forward traveling fluid

155 contained in the duct 130 until the acoustic signal reflects off of the parabolic or spherical

reflecting surface 120. The acoustic signal is then re-directed back towards the flow sensor 100

20   (flow sensor 300) until it makes a second reflection off of the end cap surface 116 (or reflective

surface 316). This reflection takes place at the reflection point 117 located on the end cap 115

midway between the central axis of the first 105 transducer and the central axis of the second

110 transducer (or at the reflection point 317 located on the reflective surface 316 of the housing

311). The acoustic signal is then re-directed back towards the parabolic or spherical reflecting surface 120 to make a third reflection. Again, the acoustic signal is then re-directed back towards the flow sensor 100 until it then passes through the end cap surface 116 (reflective surface 316) to reach the first transducer 105.

5   The curved reflecting surface 120 as shown in Figure 1 and Figure 4 may be machined or formed into an interior surface during the initial fabrication of e.g., a duct, a manifold, or a pipe. Alternatively, the curved reflecting surface 120 may be machined into an interior surface of e.g., an existing duct, manifold, or pipe in a "retrofit" process.

Figure 5 illustrates an ultrasonic sensor system 500 consisting of a duct assembly 510, an

10   ultrasonic sensor 100, a reflecting surface 120, and connectors 520. Ultrasonic sensor system 500 may be adaptable to an existing fluid system. Connectors 520 may be any type of mating connector that will provide a fluid tight seal, for example, with an existing fluid system. The reflective surface 116 of the end cap 115 is flush with an interior surface 512 of the duct assembly 510. This prevents any disturbance of a fluid flowing through the duct assembly 510.

15   Curved reflecting surface 120 may be machined into an interior surface 511 of the duct assembly 510 during the fabrication of duct assembly 510.

Figure 6 illustrates an ultrasonic sensor 100 installed into an existing duct assembly 610. Curved reflecting surface 120 may be machined into an interior surface 611 of duct assembly 610 during a "retrofit" installation of ultrasonic sensor 100 into duct assembly 610. Referring to

20   Figure 6 and Figure 7, ultrasonic sensor 100 may include a standardized mounting flange 192 including four mounting holes 193 to accommodate four mounting screws 194. The standardized mounting flange 192 replicates the mounting flange used on existing standardized fluid sensors. This aids in the retrofit process wherein an existing standardized fluid sensor may

be removed and replaced by an ultrasonic sensor 100. The end cap 115 of ultrasonic sensor 100 fitting into the existing hole in the duct assembly 610 after removal of the existing standardized fluid sensor.

Referring to Figure 8, the retrofit installation may require the machining of a reflecting

5   surface 120 into an interior surface 611 of duct assembly 610. A retrofit assembly 650, that may include precision machining equipment and a boot structure 651 with a mounting flange 652, mounts to the existing hole pattern in the duct assembly 610. The boot structure 651 serves to contain the metal shards created during a machining process preventing contamination of the existing duct assembly 610 during the retrofit process. Accurate alignment of the retrofit

10   assembly 650 may be achieved by using the mounting flange 652 in conjunction with the existing mounting holes in the duct assembly 610. A curved reflecting surface 120 may be machined into an interior surface 611 of duct assembly 610 using precision machining equipment that may be contained within the retrofit assembly 650.

Figure 9 illustrates a flow chart diagram for a method of installing an ultrasonic sensor

15   into an existing duct assembly. An existing fluid sensor is first removed 910 from an existing duct assembly. A retrofit assembly 650, that may contain precision machining equipment and a boot structure 651 with a mounting flange 652, is mounted 920 to the existing hole pattern in the duct assembly 610 using four bolts through the four bolt mounting flange 652 into the existing four mounting holes. The precision machining equipment that may be contained within the

20   retrofit assembly is inserted 930 through the existing hole in the duct assembly 610 to machine the curved reflecting surface 120. Any metal shards created during the machining process are contained within the boot structure 651. The precision machining equipment is withdrawn from the existing hole in the duct assembly 610 and a vacuum source that may also be contained

within the retrofit assembly 650 is used to remove 940 the metal shards from the boot structure 651. An ultrasonic sensor 100 is then installed 950. The end cap 115 of ultrasonic sensor 100 fitting into the existing hole in the duct assembly 610. The standardized mounting flange 192 including four mounting holes 193 accommodates four mounting screws 194 secured to the duct

5   assembly 610.

While the description above refers to particular embodiments of the present invention, it will be understood that many modifications may be made without departing from the spirit thereof. The accompanying claims are intended to cover such modifications as would fall within the true scope and spirit of an embodiment of the present invention. The presently disclosed

10   embodiments are therefore to be considered in all respects as illustrative and not restrictive, the scope of an embodiment of the invention being indicated by the appended claims, rather than the foregoing description, and all changes that come within the meaning and range of equivalency of the claims are therefore intended to be embraced therein.